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TECHNICAL NOTE

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MEASUREMENTS OF FLOW DURATION

IN A LOW-PRESSURE SHOCK TUBE

By Virgil A. Sandborn

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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MEASUREMENTS OF FLOW DURATION IN A LOW-PRESSURE SHOCK TUBE

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SUMMARY

Hot-wire signals were used to evaluate the duration of uniform flow in a shock tube. The measurements were in good agreement with similar measurements of Roshko. The similarity correlation derived by Roshko from a boundary-layer analysis was a good first-order representation of the data; however, at the extreme low pressures a systematic deviation from the correlation was noted.

INTRODUCTION

The shock tube is a useful tool in the study of high Mach number, high-temperature gas flow. In this study a shock wave is caused to travel down the tube by the rupture of a diaphragm between a high- and a low-pressure gas. The shock wave compresses the gas directly behind the wave into a slug of extremely high-temperature gas. The slug of compressed gas is contained between the shock wave and a contact surface, which marks the boundary between the gases that were initially on either side of the diaphragm. With a fixed probe in the shock tube, the duration of uniform flow in the ideal case is defined as the period of time between the arrival of the shock and the arrival of the contact surface. The flow duration decreases as the shock Mach number and the density ratio across the shock increases; however, recent experimental evidence reported by Duff (ref. 1) and Roshko (ref. 2) show that the flow duration of low-pressure shock tubes is a great deal shorter than that predicted by the ideal gas theory. Roshko has formulated an analysis whereby fluid in the boundary layer leaks past the contact surface and decreases the flow duration. Roshko's measurements are well correlated with the analysis; the data of Duff, however, show a greater decrease in flow duration and are not correlated by the analysis of Roshko.

The measurements described herein were obtained in the course of an experimental program to evaluate the hot-wire resistance-temperature transducer for use in shock tubes.

SYMBOLS

a	speed of sound
d	diameter of shock tube
$F(M_s)$	function of shock Mach number, $\frac{1}{Z_2} \frac{T_2}{T_1} \frac{(\rho_2/\rho_1) - 1}{\rho_2/\rho_1} \frac{1}{M_s}$
$G(M_s)$	function of shock Mach number, $\frac{1}{Z_2} \frac{T_2}{T_1} \frac{\left[(\rho_2/\rho_1) - 1\right]^2}{\rho_2/\rho_1}$
l	distance from diaphragm to measuring station
M	Mach number
P	pressure
T	gas temperature
$\mathcal{T}$	nondimensional time-similarity parameter, eq. (2)
u	velocity
X	nondimensional distance-similarity parameter, eq. (3)
x	coordinate measured along length of shock tube
Z	compressibility factor
β	boundary-layer parameter depending on conditions outside boundary layer, eq. (4)
δ	boundary-layer displacement thickness, eq. (4)
λ	mean free path
ρ	density of gas
τ	flow duration

Subscripts:

i	ideal
s	shock, static

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w wall

1 conditions in shock tube before shock

2 conditions in shock tube after shock

TEST SETUP AND PROCEDURE

Shock Tube

A 2.9-inch-diameter tube 25 feet long was employed for the measurements presented herein. The last 5 feet of the tube was square for model testing. The high-pressure driver gas section was of the same diameter and 64 inches long. Soft copper diaphragms were employed. The diaphragms were unscribed and were broken by a star drill. The thickness of the diaphragm was varied with the driver gas pressure. Room air, argon, and nitrogen were used as the driven gas. The driver gas used was helium.

Resistance-Temperature Transducers

Surface film gages and hot-wire resistance-temperature transducers were employed in the tests. The film gages were used to time the shock speed along the tube. A 0.0004-inch-diameter platinum-iridium wire was used to detect the passage of the shock wave and the contact surface. For the measurements reported, the wire was located in the center of the shock tube and soft soldered to stainless-steel supports 0.083 inch apart.

When the shock passed, the transducers were surrounded by a very high-temperature gas. This condition caused an increase in resistance of the transducers. An electrical output was obtained by operating the transducers as one arm of a Wheatstone bridge, and the unbalance of the bridge or the voltage change across the transducer was measured. The voltage measured can be related to the increase in resistance and further to the temperature and heat transfer experienced by the transducer (e.g., ref. 3). The speed with which the transducers can respond to the sudden increase in surrounding temperature and heat transfer depends on their physical dimensions and properties. For the elements employed in these measurements, the response was so slow that the final temperature reached was only a small percentage of the gas temperature. In any case the transducers began to heat as soon as the shock passed in an exponential rise (which for very small times appeared as a linear rise). Any change in the nearly linear heating curve indicates a change in the surrounding temperature and/or velocity has occurred; thus, the transducer indicated the time of uniform flow even though the temperature of the flow was never obtained.

The hot-wire measurements were made at stations 17.7 and 18.7 feet downstream from the diaphragm. The film gages were mounted at several locations along the length of the tube to establish the progress of the shock down the tube. The output of both types of gage was recorded with calibrated oscilloscopes.

RESULTS AND DISCUSSION

The ranges of pressures and Mach numbers of the data are shown in figure 1 where the driver gas was helium and the driven gas was room air. The measuring station for the data of figure 1 corresponds to the location of interest in the hot-wire measurements.

Figure 2 demonstrates the variation of shock Mach number along the length of the tube. These data were of particular interest since the theory of Roshko (ref. 2) depends on the total transit time of the shock from the diaphragm to the measuring station. From a linear extrapolation of the Mach numbers of figure 2 back to the diaphragm, it was calculated that no correction for shock attenuation along the tube was necessary. This conclusion, of course, will be true only for the particular case, since a different location or different shock tube could lead to a correction. The cause of the nonuniform shock velocity was not determined.

Typical oscilloscope recordings of hot-wire outputs are shown in figure 3. The time scale is the same for all traces; however, the voltage scale is different. A definite change in heat-transfer rate is evident in each trace. For the two lowest pressure runs (105 and 100 microns Hg; micron = 10^{-6} meter) the duration of uniform flow is very short and represents a very small part of the trace. In some cases the voltage output of the wire continues to rise after the contact surface arrives. This rise corresponds to the continued heat transfer from the wire due to the gas velocity and does not indicate that the temperature behind the contact surface is greater than the original temperature.

Figure 4 shows the actual observed flow duration for different initial pressures of the driven gas. Since no marked difference was observed between the different gases, it was evident that energy-state phenomena, such as vibrational relaxation, are not causing the break in the heating curves. Further, relaxation would not be affected by pressure in the manner noted. Thus, it can only be concluded that the contact surface is being observed.

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The flow duration for an ideal gas in a shock tube is given by the equation (ref. 2)

$$\tau_i = \frac{x}{a_1 M_s[(\rho_2/\rho_1) - 1]} \tag{1}$$

where τ_i is the time, x is the distance from the diaphragm, a_1 is the speed of sound in the undisturbed gas, M_s is the shock Mach number u_s/a_1, and ρ_2/ρ_1 is the density ratio across the shock. Figure 5 shows a plot of the measured Mach number and values of ρ_2/ρ_1 from nonideal gas calculations (ref. 4), in terms of $\frac{1}{M_s[(\rho_2/\rho_1) - 1]}$ against the diaphragm pressure ratio. From equation (1) note that $\frac{1}{M_s[(\rho_2/\rho_1) - 1]}$ is equivalent to $\tau_i a_1/x$. The actual observed values of $\tau_i a_1/x$ are also included in figure 5. The theoretical flow duration is an order of magnitude greater than observed times for the low pressure flows (largest diaphragm pressure ratios). As the driven gas pressure increases the actual flow duration approaches the theoretical time.

The concept that the low-speed gas in the boundary layer near the wall leaks past the contact surface was proposed by Duff (ref. 1) and also by Anderson (ref. 5). Roshko (ref. 2) has obtained a relation between a nondimensional flow duration and a nondimensional distance parameter from the laminar-boundary theory. These similarity parameters

$$\mathcal{T} = 16\left(\frac{u}{\rho a}\right)_s \beta^2 G(M_s) \frac{P_s}{P_1} \frac{a_1 \tau}{d^2} \tag{2}$$

and

$$X = 16\left(\frac{u}{\rho a}\right)_s \beta^2 F(M_s) \frac{P_s}{P_1} \frac{x}{d^2} \tag{3}$$

come from the laminar-boundary-layer analysis, in which the boundary-layer displacement thickness is given by

$$\delta = \beta\left(\frac{u l}{\rho_w u_2}\right)^{1/2} \tag{4}$$

From this "mass flow defect thickness" the amount of mass flowing past the contact surface may be calculated. The resulting relation may be expressed in terms of $\mathscr{T}$ and X as

$$\frac{X}{2} = -\ln\left(1 - \sqrt{\mathscr{T}}\right) - \sqrt{\mathscr{T}} \tag{5}$$

For the ideal gas shock tube the equation relating X and $\mathscr{T}_i$ is simply

$$X = \mathscr{T}_i \tag{6}$$

Figure 6(a) is a plot of equations (5) and (6) in the range of interest of this experiment. The measurements of Roshko (ref. 2) and of this report are included in figure 6(a). The value $16(u/\rho a)_s \beta^2 \rho_s = 0.0650$ for air given by Roshko was employed in the evaluation of $\mathscr{T}$ and X for data. The measurements are in good agreement with those of Roshko. The qualitative agreement with equation (5) is good, although the data suggest a systematic departure at large values of X.

The measurements reported by Duff (ref. 1) are shown in figure 6(b). These data are compared with the measurements by Roshko and this experiment. In all cases of figure 6(b), the driven gas is argon and not air. Duff used a $1\frac{1}{8}$-inch-diameter shock tube, which is much smaller than the shock tube used in this investigation or those of Roshko. An electron-gun densitometer was used to detect the shock and contact surface instead of the hot wires employed in these and Roshko's measurements. It may be that the integrating effect of the densitometer observes an increase in density near the wall not observed by the hot wires in the center of the tube. Hot wires mounted at different distances from the wall in the experiments failed to indicate any great variation in flow duration. It was possible that the flow duration was reduced by 20 percent or less at a point 1/2 inch from the wall as compared with that at the center; however, the accuracy of the present measurements is not adequate to establish more than a trend toward the shorter flow duration. The results are in the same direction as would be suggested by Duff's measurements.

Since the flow duration reduction occurred at low pressures, slip flow phenomenon may have occurred. The deviation of the observed flow duration from the predictions of Roshko (eq. (5)) are plotted in figure 7 against the slip flow parameter, the Knudsen number. The Knudsen number employed is the ratio of the mean free path of a molecule of the driven gas to the computed displacement thickness of the boundary layer. The Knudsen number range shown in figure 7 is approaching the slip flow

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region. While Roshko (ref. 2) was able to argue that β of equation (4) will vary little with Mach number, it may be that β varies in such a manner with the Knudsen number as to explain the trend shown in figure 7. The definition of the Knudsen number is also vague since β appears in the value of δ. It appears that the continuum solution obtained by Roshko is adequate as long as the Knudsen number does not exceed 0.01 or 0.02.

SUMMARY OF RESULTS

The experimental observations of shock-tube flow duration described in this report agree with similar measurements of Roshko. The similarity parameters and correlation of Roshko are a good first-order representation of the data presented herein. At the very low driven gas pressures, a systematic trend away from Roshko's predictions suggests that slip flow effects may also have to be considered.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 5, 1961

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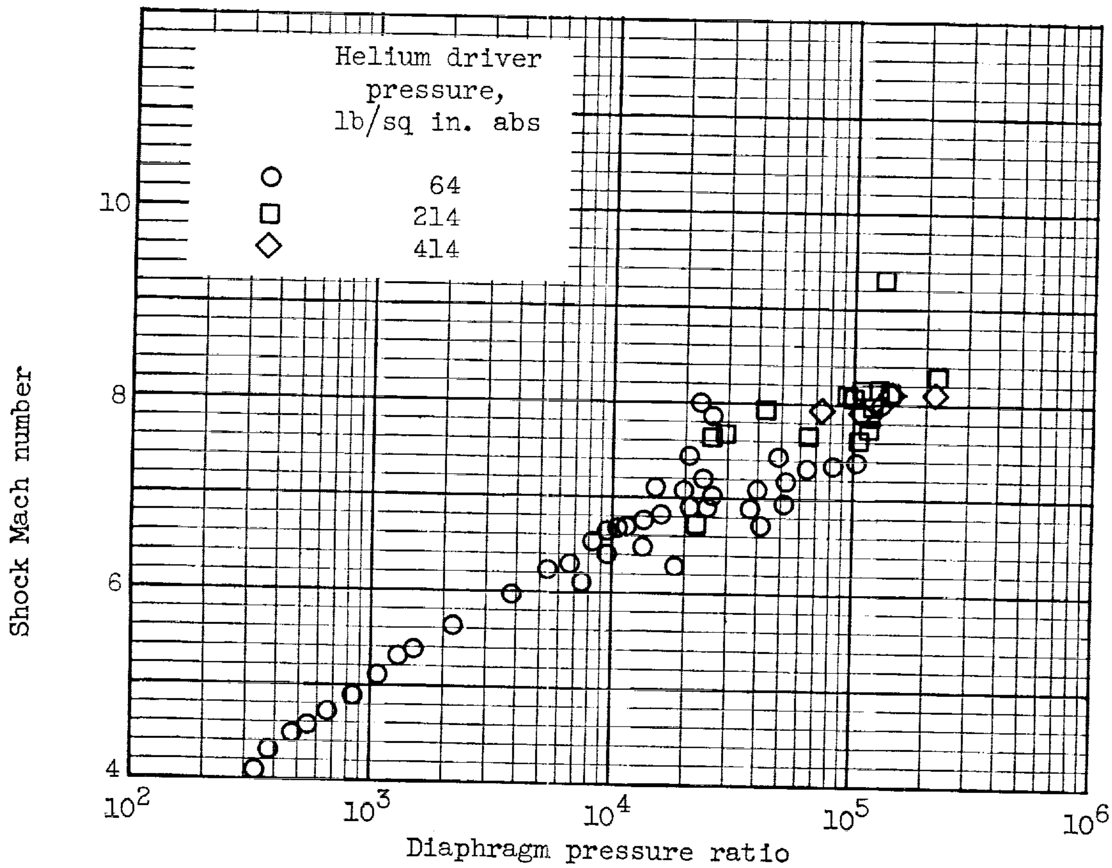

Figure 1. - Observed variation of shock Mach number with pressure ratio across diaphragm of 2.9-inch-diameter helium-air shock tube. Observations made at distance of 17.2 feet downstream from diaphragm.

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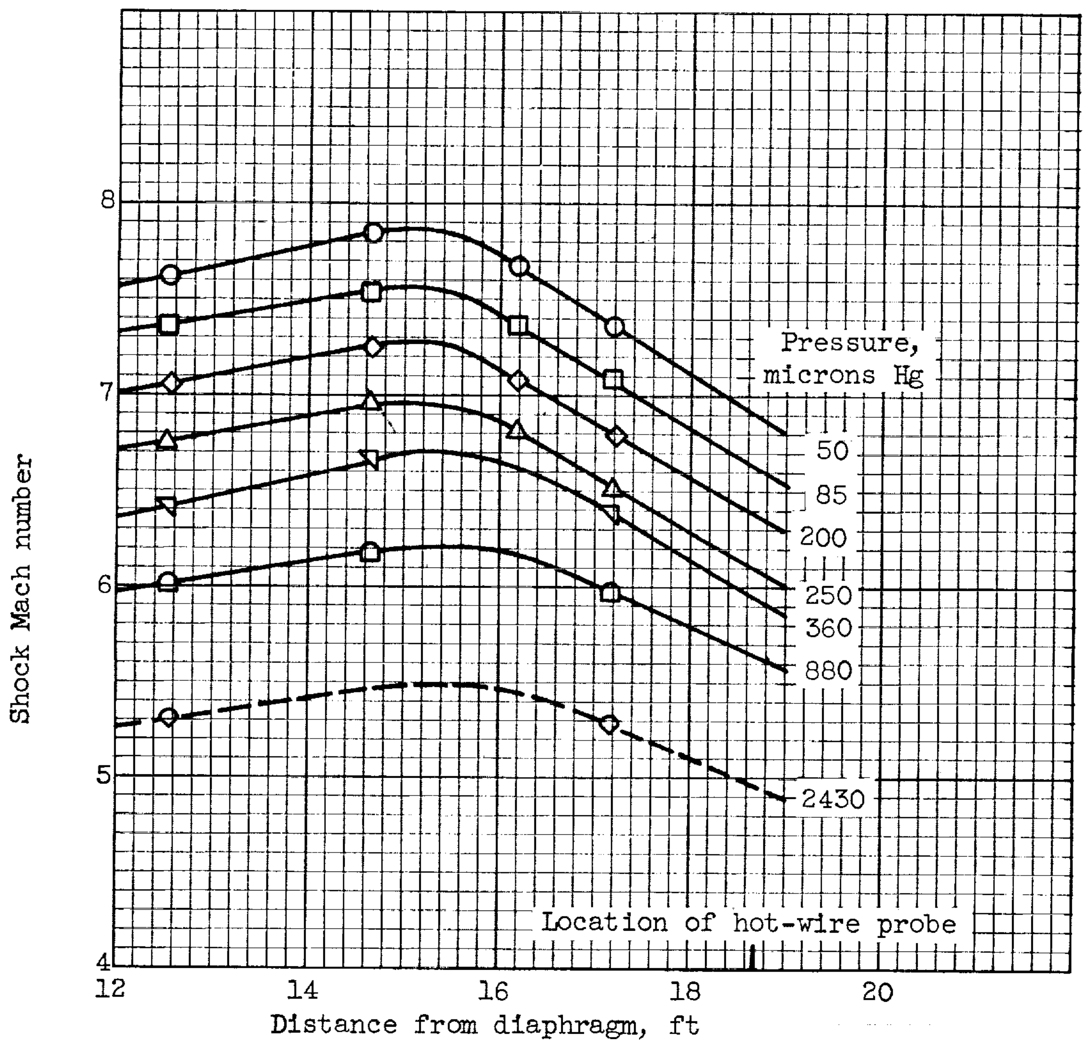
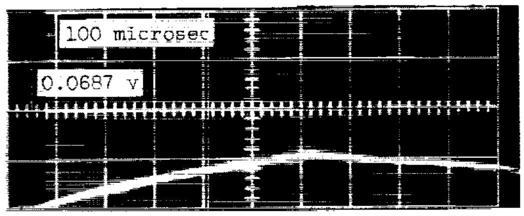
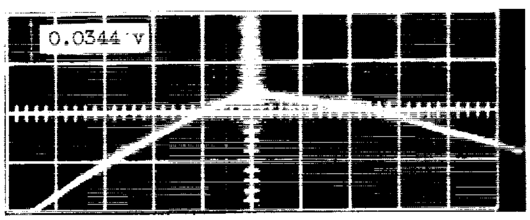


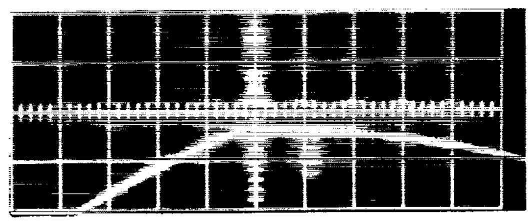
Figure 2. - Variation of shock Mach number along shock tube. Driver gas, helium at 64 pounds per square inch absolute; driven gas, air.



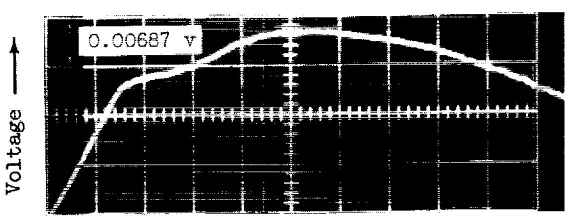
Shock Mach number: 3.87
Static pressure before shock: 9.82×10^3 microns Hg
Static pressure behind diaphragm: 64 lb/sq in. abs



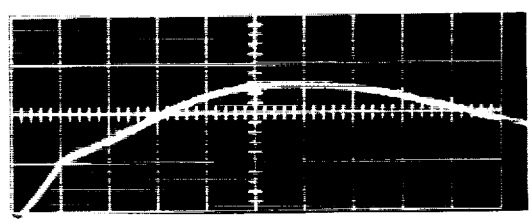
4.51
4.95×10^3 microns Hg
64 lb/sq in. abs



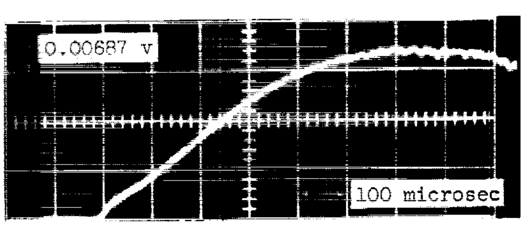
5.00
2.44×10^3 microns Hg
64 lb/sq in. abs



5.90
630 microns Hg
64 lb/sq in. abs

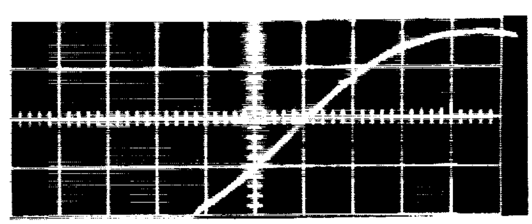


6.28
290 microns Hg
64 lb/sq in. abs



7.16
105 microns Hg
214 lb/sq in. abs

Time



7.59
100 microns Hg
414 lb/sq in. abs

Figure 3. - Typical oscilloscope recordings of hot-wire voltages.

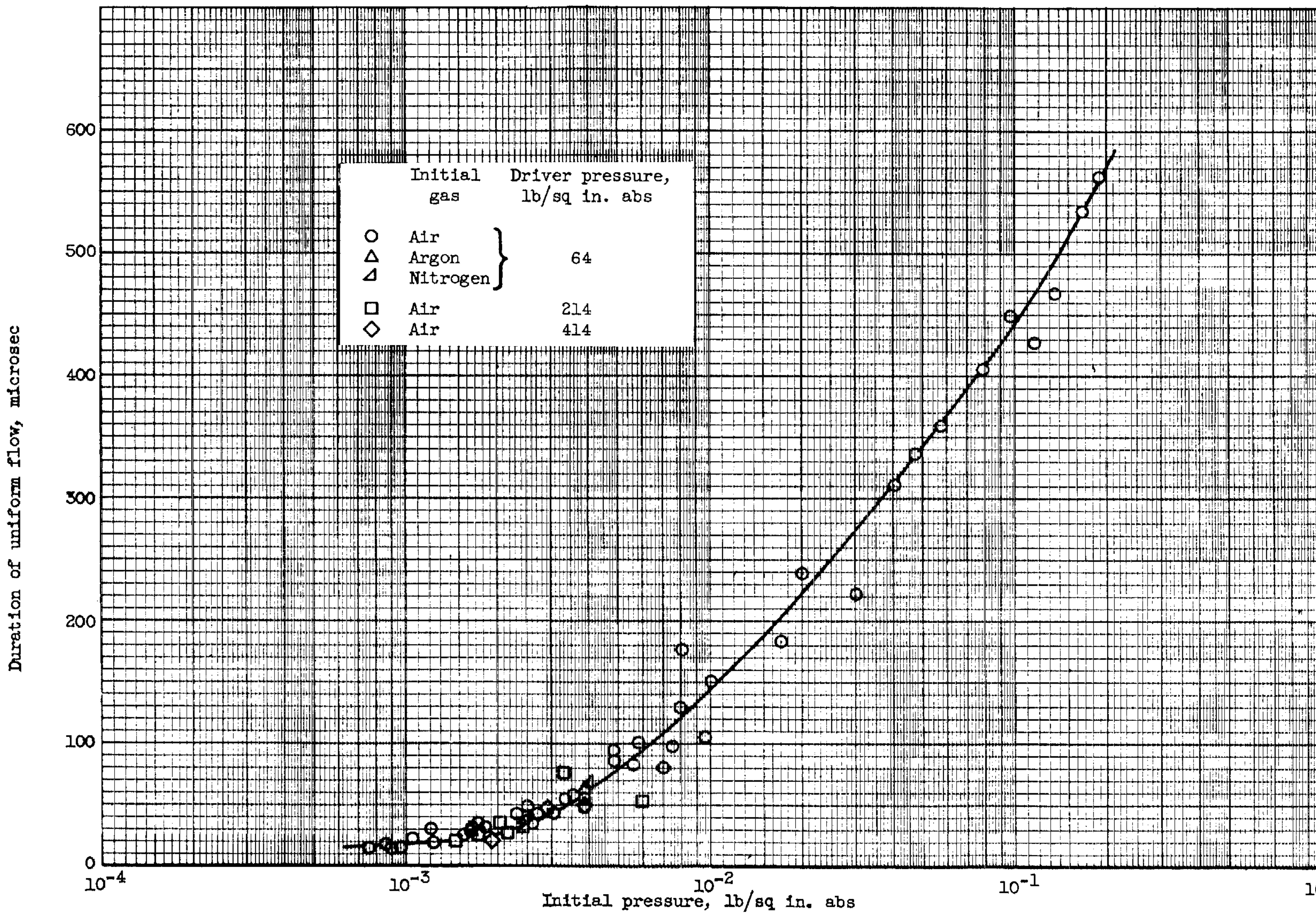


Figure 4. - Variation of flow duration with tube pressure. Measuring station, 18.7 feet downstream from diaphragm. Driver gas, helium.

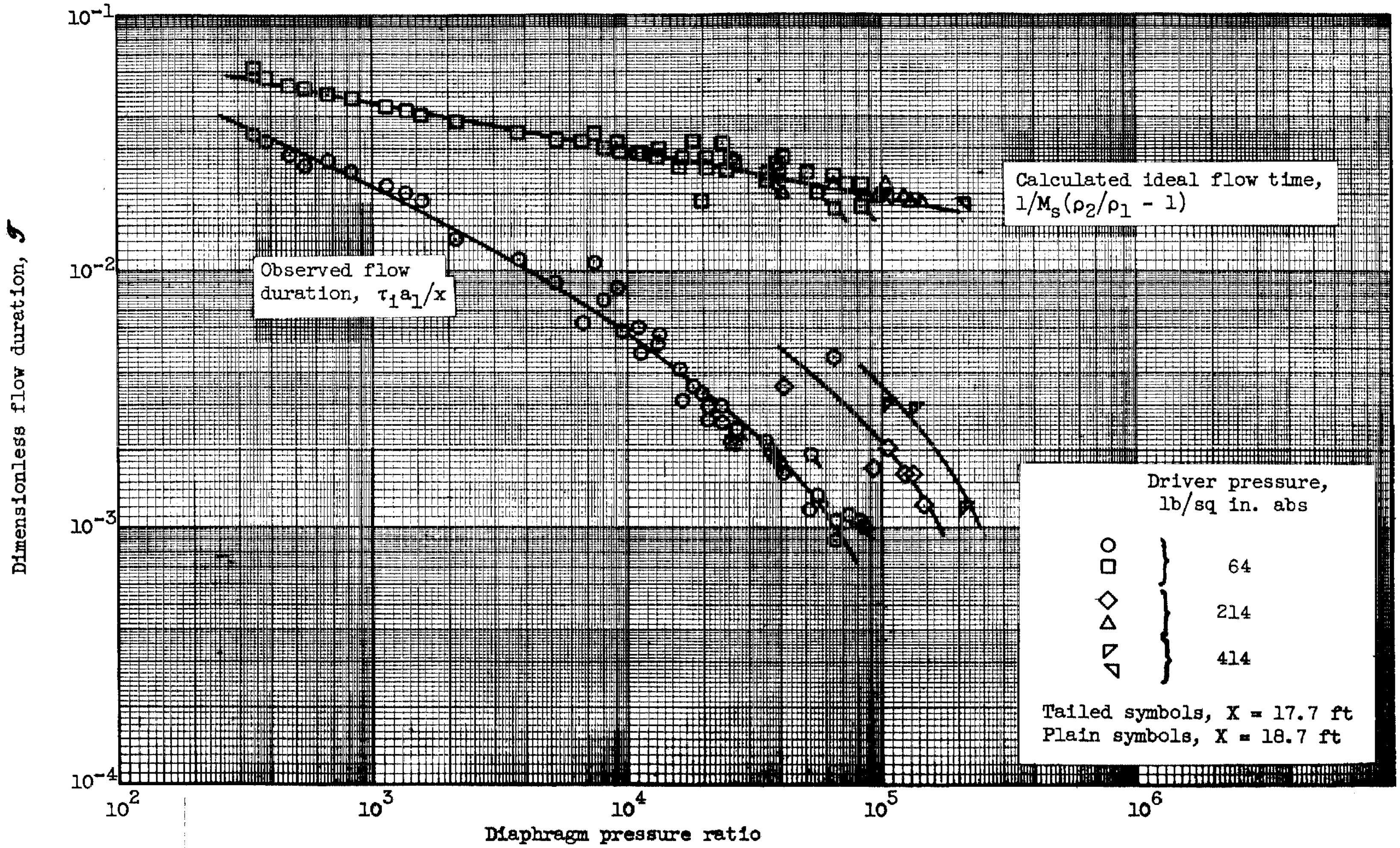


Figure 5. - Comparison of observed flow duration time in 2.9-inch-diameter shock tube with ideal time. Driver gas, helium; driven gas, air.

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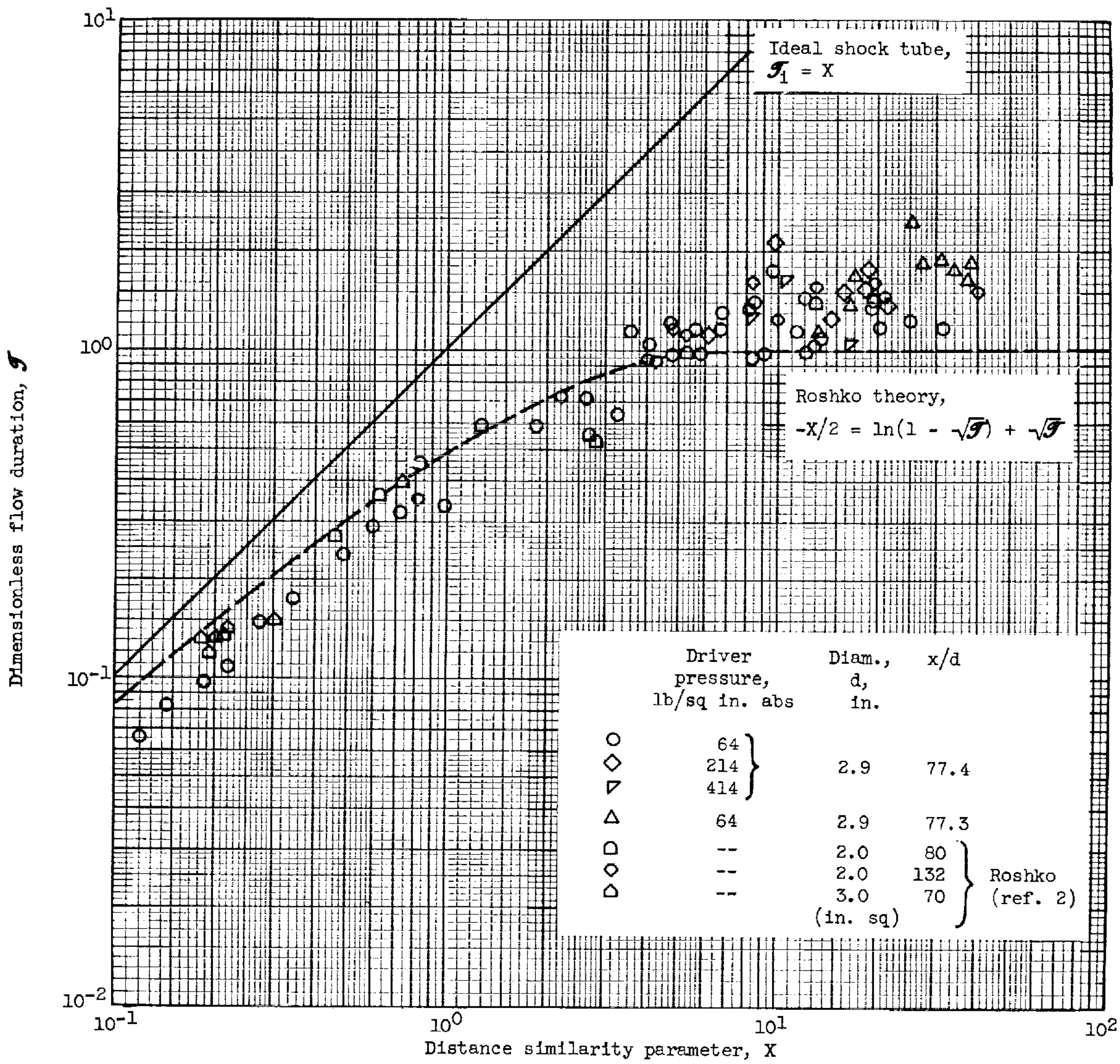
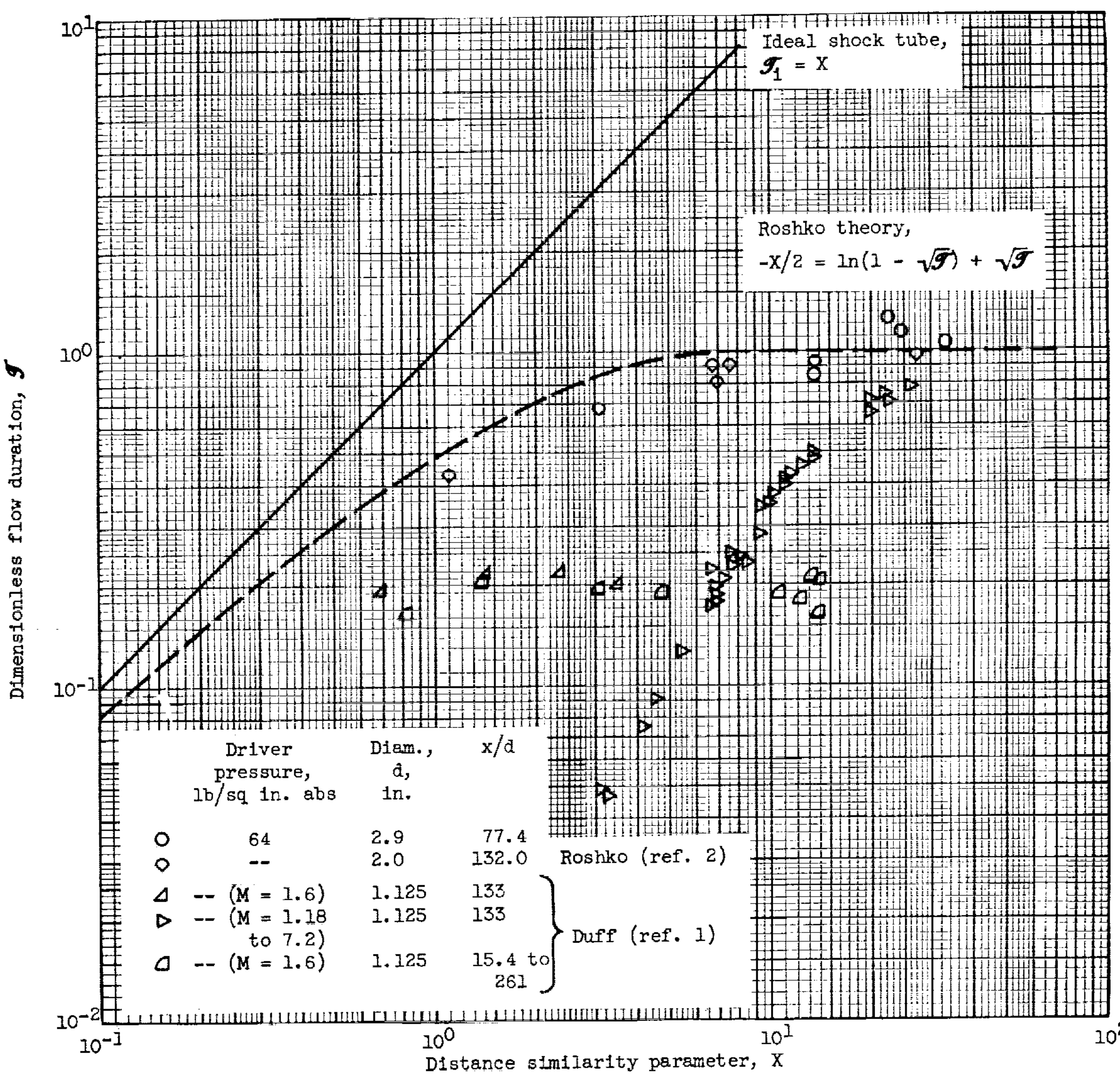


(a) Driven gas, air.

Figure 6. - Dimensionless flow duration and distance similarity parameters for shock tube according to Roshko.



(b) Driven gas, argon.

Figure 6. - Concluded. Dimensionless flow duration and distance similarity parameters for shock tube according to Roshko.

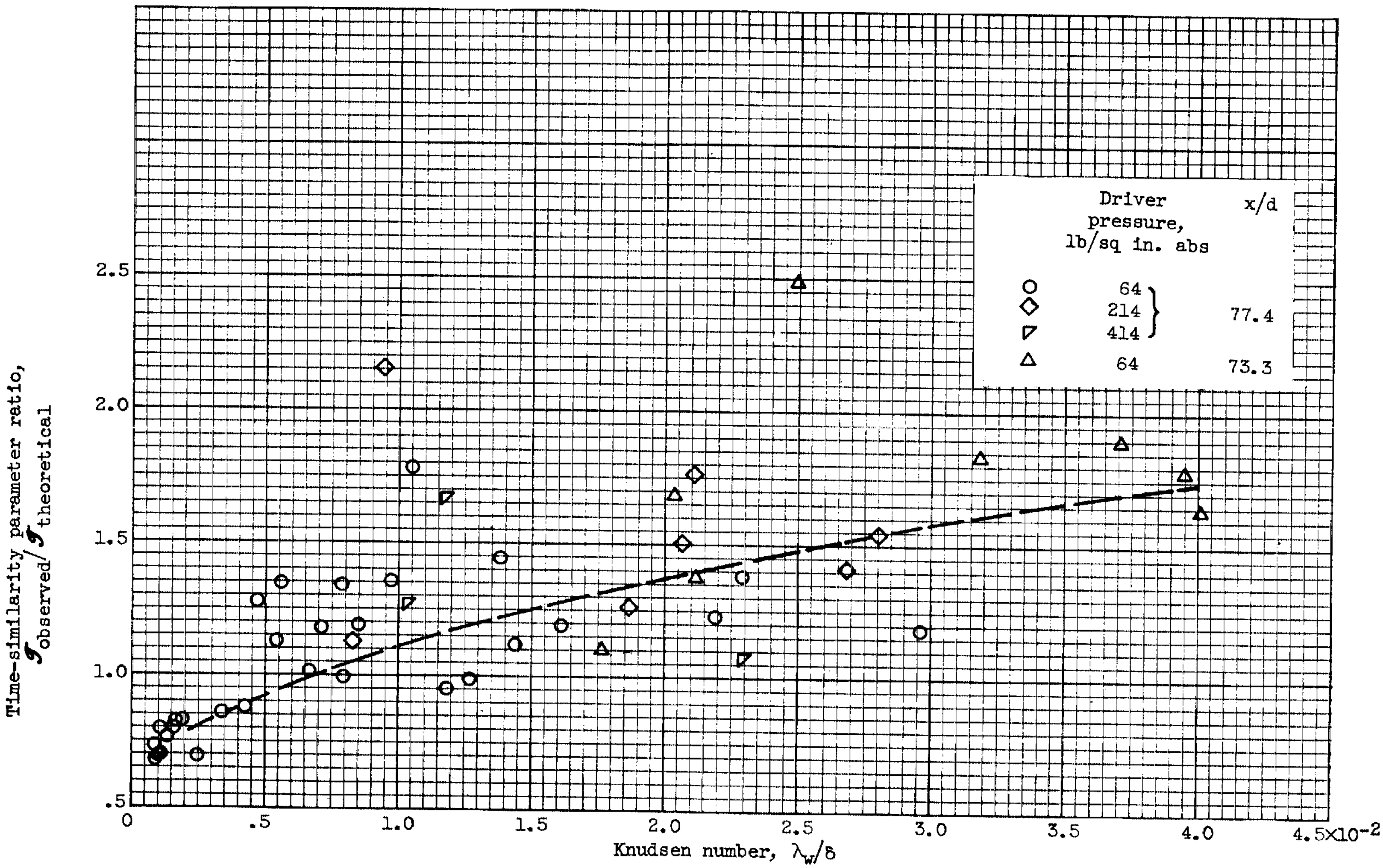


Figure 7. - Comparison of deviations of observed flow duration from theory with slip flow parameter, Knudsen number.

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